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Production of hot near-solid-density plasma by electron energy transport in a laser-produced plasma

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Targets with a layer of aluminum buried beneath a plastic overlay have been irradiated with 0.53-μm wavelength, 20-ps pulse length light at $(1-2)\times10^{16}$ W cm^{-2}. The widths of Stark broadened Al XII $1s^2\,{}^1S_0$–$1s3p\,{}^1P_1$ spectral lines and the ratios of satellite line intensities to the Al XII $1s^2\,{}^1S_0$–$1s2p\,{}^1P_1$ spectral line emitted from the aluminum layer imply electron densities up to $(6-8)\times10^{22}$ cm^{-3}. This result is a direct observation of significant energy transport to densities close to solid.

The process of energy transport and ablation when laser radiation is absorbed at a surface to form a plasma has been studied extensively for conditions where the hydrodynamic flow pattern approaches a steady state[1] and heating occurs at densities close to the critical density. However, when the laser pulse duration is less than the hydrodynamic response time, electron thermal conduction heats matter at close to solid density.[2]

In x-ray laser research there is a need for plasmas with simultaneous high temperature, high density, and high degree of ionization.[3] Consideration of this requirement and the intrinsic interest in such plasmas has led us to undertake short-pulse laser-plasma experiments with targets of a thin layer of aluminum buried beneath a confining plastic overcoat. In this paper, we show that a hot, dense, and well-ionized aluminum plasma can be produced in the buried layer.

An experiment was carried out with 20-ps pulses from the VULCAN laser at 0.53-μm wavelength in a single beam at energies of 6–8 J focused to a 50-μm focal spot giving intensities of $(1-2)\times10^{16}$ W cm^{-2}. The energy transport was recorded using layered targets designed to show the following. (i) The penetration of heating into the solid evidenced by the emission spectrum of the Al layer buried below the plastic layer. The aluminum layer was thin enough (0.2 μm) to permit measurement of a time-averaged electron density and temperature from optically thin H-like to Li-like Al spectra features. All spectral lines except the Al H-like $1s$-$2p$ and He-like $1s^2\,{}^1S_0$–$1s2p\,{}^1P_1$ resonance lines are optically thin. These lines have an optical depth estimated for the experimentally determined plasma parameters and Al layer thickness to be at most unity in the direction of the target normal. (ii) The penetration of hot electrons and their preheating effect from more deeply buried $K\alpha$ fluors of KCl and CaF_2.

From the target surface to the inner layers, the target layer composition was plastic (CH) ablator of thickness 0 to 1 μm; Al, 0.2 μm; CH, 2.5 to 5 μm; KCl, 2 μm; CH, 5 μm; CaF_2, 2 μm; with a substrate of 10-μm Mylar. The targets were flat disks of 300-μm diameter. Aluminum resonance lines have insufficient photon energy to photoexcite the $K\alpha$ fluors (Cl, K, and Ca). Radiative preheating of the aluminum layer is negligible relative to that produced by the electron thermal-conduction wave as the surface plastic overlay is a weak emitter.

Two x-ray spectrometers were used. A flat crystal spectrometer of moderate spectral resolution ($\lambda/\Delta\lambda\sim1000$) with a diffracting crystal of Pentaerythritol (PET) ($2d=8.742$ Å) was used to monitor K emission from Cl, K, and Ca to the He-like and H-like lines of aluminum in the wave band 3.5–7.3 Å. A Johann-type PET crystal spectrometer with high resolving power ($\lambda/\Delta\lambda\sim7000$) was used to observe the $n=2$ to $n=1$ transitions of the He-like and H-like Al ions in the wave band 7.0–7.9 Å. The spectra were recorded on Kodak direct exposure film. Spectral intensities have been determined after converting the optical densities on film to intensities using the calibration given by Henke *et al.*[4]

The Stark broadened spectral widths of the helium-like aluminum line Al XII $1s^2\,{}^1S_0$–$1s3p\,{}^1P_1$ is a sensitive indicator of electron density for densities $\gtrsim10^{22}$ cm^{-3}. In Fig. 1 calculations using the code of Lee[5] are shown. The jump in the "zero" instrument broadening curve of Fig. 1 is due to the double-hump nature of the Stark line profile. For the flat-crystal spectrometer, the expected instrument broadening is 6 mÅ (the solid curve of Fig. 1) caused primarily by the finite ($\simeq50$ μm) diameter of the plasma. Satellites to the hydrogen-like Lyman-α line are expected to be broadened mainly by instrumental effects and indeed

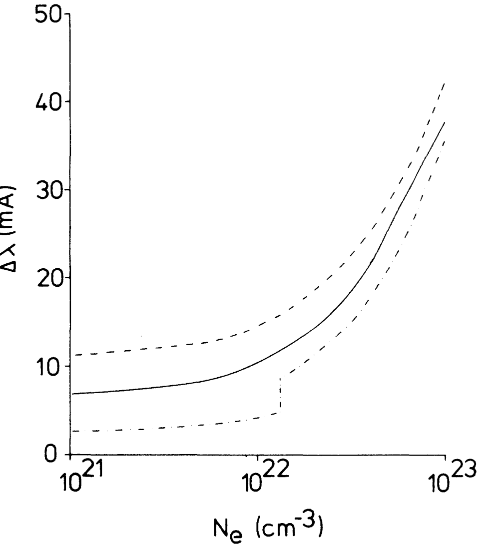

FIG. 1. Calculated full width at half maximum $\Delta\lambda$ of the aluminum heliumlike line $1s^2\,{}^1S_0$–$1s3p\,{}^1P_1$ as a function of electron density N_e. Doppler broadening is taken into account assuming an ion temperature of 500 eV, and instrumental broadening is taken into account assuming an instrument full width at half maximum of 10.7 mÅ (dashed curve), 6 mÅ (solid curve), and zero (dashed-dotted curve).

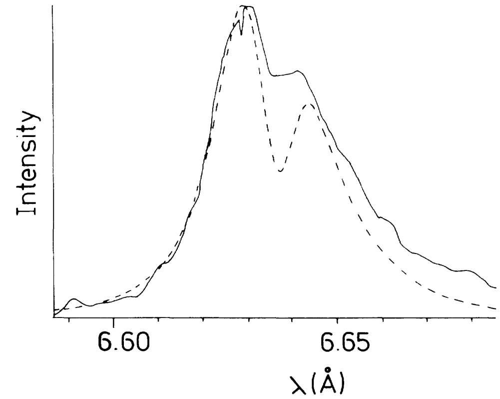

FIG. 2. Experimental spectral line profile of Al XII $1s^2\,{}^1S_0$–$1s3p\,{}^1P_1$ (solid curve) fitted with a theoretical profile (dashed curve) assuming $N_e = 6\times10^{22}$ cm^{-3}, an ion temperature of 500 eV, and instrument broadening of 6 mÅ. The experimental profile is emitted from an aluminum layer buried 0.5 μm below a plastic overcoat.

we have measured with the flat crystal spectrometer their full widths at half maximum to be approximately 6 mÅ. Doppler broadening (provided the ion temperature is less than 2 keV) does not significantly affect the measured line profiles with our instrument resolution.

Detailed comparisons of the Stark line shape predicted by Lee[5] and the experimentally measured line shape show excellent agreement (Fig. 2). In Fig. 2, the fit is optimized for the lower wavelength wing of the spectral line as there are satellite lines (in particular the intercombination line Al XII $1s^2\,{}^1S_0$–$1s3p\,{}^3P_1$) on the higher wavelength wing of the line. The electron density giving the best fit in this Fig. 2 example is 6×10^{22} cm^{-3}, a value significantly above the laser critical density of 4×10^{21} cm^{-3}. An aluminum plasma composed of fully stripped ions at solid density would have an electron density of 7.8×10^{23} cm^{-3}.

The intensity ratios of satellite lines to the heliumlike aluminum line Al XII $1s^2\,{}^1S_0$–$1s2p\,{}^1P_1$ can also be used to deduce electron densities. The satellites q, r, a–d, and j, k, l (labeled according to Gabriel[6]) emitted from an uncoated aluminum target and from an aluminum layer buried 0.5 μm under plastic are shown in Fig. 3. The a–d satellite group shows enhancement in the buried layer emission indicating[7] a higher electron density than for the uncoated aluminum emission. Using the tabulations of Jacobs and Blaha,[7] the spectrum [Fig. 3(a)] from the uncoated target indicates an electron density of 5×10^{22} cm^{-3}, while the spectrum [Fig. 3(b)] from the buried layer target implies an electron density of 8×10^{22} cm^{-3}.

Electron densities in the aluminum layer determined from the spectral width of the Al XII $1s^2\,{}^1S_0$–$1s3p\,{}^1P_1$ line (deduced using Fig. 1) and electron densities determined from the intensity ratios of the a–$d+q$, r to j, k, l satellite lines of Al XII $1s^2\,{}^1S_0$–$1s2p\,{}^1P_1$ (deduced using the tabulations of Jacobs and Blaha[7]) are shown in Fig. 4. The electron densities at the inner and outer boundaries of the aluminum layer at the end of the laser pulse predicted by MEDUSA (Ref. 8) one-dimensional fluid-code simulations are also plotted on Fig. 4. In these simulations, the laser intensity is 2×10^{16} W cm^{-2} and 5% of the laser light reaching the critical density is assumed dumped to thermal electrons and 5% to superthermal electrons.

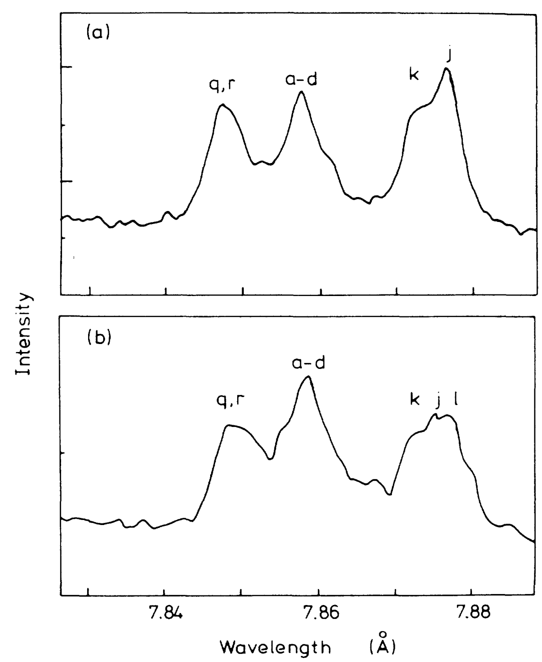

FIG. 3. Satellite lines to the Al XII $1s^2\,{}^1S_0$–$1s2p\,{}^1P_1$ resonance line labeled according to Gabriel (Ref. 6) emitted from (a) an uncoated aluminum target and (b) an aluminum layer buried 0.5 μm under plastic.

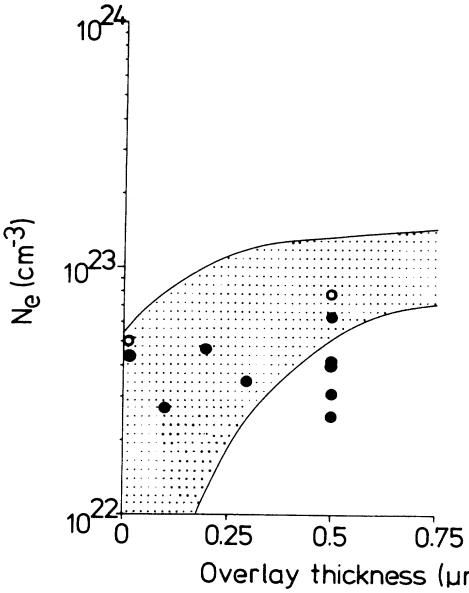

FIG. 4. Electron densities measured (i) from the width of the Al XII $1s^2\,{}^1S_0$–$1s3p\,{}^3P_1$ spectral line (filled circles) and (ii) from the ratio of the intensity of the Al XII $1s^2\,{}^1S_0$–$1s2p\,{}^1P_1$ satellites $I(a\text{-}d+q,r)/I(j,k,l)$ (open circles) as a function of the thickness of plastic overlay on top of the aluminum layer. The shading shows the range of electron densities predicted by the MEDUSA code from the inner (top curve) to the outer (bottom curve) boundaries of the aluminum layer at the end of the laser pulse.

From the slopes of linewidth as a function of electron density plotted in Fig. 1 and uncertainty in the flat crystal wavelength resolution, the Stark broadening measurements of electron density over the range 10^{22}–10^{23} cm^{-3} are estimated to be accurate to within ±20%. It is difficult to assess the accuracy of the electron densities deduced from the satellite line intensity ratios. The density sensitivity of the satellite line intensities is largely determined by $\Delta n = 0$ collision rates. Plasma effects can alter these $\Delta n = 0$ cross sections more readily than $\Delta n \neq 0$ cross sections[9] and may be a source of systematic error in using the results of Jacobs and Blaha.[7] Given such uncertainties of doubly excited population modeling, the errors in deducing electron densities from satellite line intensities are likely to be significantly worse than ±20%.

Helium- and hydrogenlike aluminum spectra and their satellites were produced with up to 0.75 μm overlay thickness, but the linewidths and satellite line intensities and hence electron densities could only be accurately measured with overlay depths up to 0.5 μm because of the low intensity of the lines with 0.75 μm overlay depth. The spectral intensities were approximately constant for the He-like lines for all overlay depths up to 0.5 μm, but for the H-like lines, the intensities dropped by a factor of ≃3 from zero overlay to 0.5 μm thickness overlay.

Kα emission of K and Cl was observed, but not of the higher atomic number Ca. This implies that the superthermal electron temperature is less than ~10 keV.[10] The slope of the hard-x-ray continuum between 5 and 20 keV measured by a filtered diode array indicated a temperature of 6±2 keV. The measured absolute flux of K *Kα* emission was $\simeq 2.5\times10^{-17}$ J/sr which, using the analysis of Hares *et al.*,[10] implies that the total superthermal electron energy (temperature ≃6 keV) was approximately 0.3 J. This is about 5% of the incident laser energy. Thermal electron temperatures in the aluminum layer have been determined from the slope of the He-like free-bound continuum measured by the flat crystal spectrometer. The temperatures are estimated to be ~1 keV for all plastic overlay thicknesses from 0.1–0.5 μm. With larger overlay thicknesses, the intensity of the free-bound continuum was not sufficient for an accurate temperature measurement.

Pinhole camera pictures show that the spatial extent of emission in the 7.95–18-Å band (passing through a 10-μm Al filter) is localized to within 50–70 μm. There is no evidence for plasma formation outside the laser focal spot area as has been reported for laser wavelengths ≥1 μm.[11–13] The area over which hot electrons produce *Kα* radiation, however, was not measured.

We have shown that hot (~1 keV), dense [~(6–8) $\times10^{22}$ cm^{-3}] and well-ionized plasmas can be produced from a layer buried under a plastic overcoat irradiated by short pulse (20 ps), high intensity (~10^{16} W cm^{-2}), 0.53 μm laser light. The temperature and energy content of the superthermal electrons is small (6 keV and 5% of laser energy, respectively). Our observation of a significant drop in emission from the buried layer once the overcoat thickness exceeds 0.5 μm implies that the buried layer plasma is produced by thermal conduction. Superthermal electron "preheating" of the buried layer would fall off more slowly with increasing overlay thickness.

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